

IMAGES OF HCO^+ (1–0) EMISSION IN A MOLECULAR CLOUD NEAR 1E 1740.7–2942

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Received 1994 October 25; accepted 1995 January 5

ABSTRACT

We have observed the hard X-ray source 1E 1740.7–2942 in the HCO^+ (1–0) line using the Owens Valley millimeter interferometer. Previous single-dish observations have found HCO^+ emission coincident with the location of the radio continuum hot spots of the radio source associated with 1E 1740.7–2942. Our higher resolution observations show a $15''$ offset between the HCO^+ emission and the location of the radio hot spots. We propose that the lack of emission results from a large ionization rate, exceeding 10^{-15} s^{-1} , in the neighborhood of 1E 1740.7–2942.

Subject headings: gamma rays: observations — ISM: general — ISM: jets and outflows — X-rays: general

1. INTRODUCTION

The Galactic center region is a luminous source of 511 keV X-ray line emission resulting from electron-positron annihilation. The line has two components: a diffuse and steady component resulting from annihilation of positrons produced by novae and supernovae in the interstellar medium and a time-variable component, long believed to originate in a black hole or neutron star, dubbed the “Great Annihilator” (Lingenfelter & Ramaty 1988). The properties of the time-variable line indicate that the annihilation region is small, less than 10^{18} cm , dense, $n_{\text{H}} > 10^5 \text{ cm}^{-3}$, and cold, $T < 5 \times 10^4 \text{ K}$. This annihilation environment is very different from the high-energy environment in which the positrons are produced, e.g., an accretion disk near a black hole, and there is considerable interest in identifying the source of the positrons.

The hard X-ray source 1E 1740.7–2942 (Sunyaev et al. 1991) is a strong candidate for the positron source. The emerging picture of 1E 1740.7–2942 is the following (Chen, Gehrels, & Leventhal 1994; Mirabel 1994): it is a compact object, probably a stellar-mass black hole, on the edge of a molecular cloud (Mirabel et al. 1991; Bally & Leventhal 1991). The high-energy emission arises from an accretion disk with instabilities giving rise to pair production and annihilation, which in turn produces the excess above 300 keV. The accretion disk collimates some of the pairs to form jets which are visible as bipolar radio lobes (Mirabel et al. 1992). The pairs in the jets travel about 1 pc before slowing and thermalizing in the cold, dense environment of the molecular cloud where any remaining positrons are annihilated.

The details of this picture are controversial. It is not clear whether the source of accreted material is a stellar companion or perhaps the molecular cloud itself (Campana & Mereghetti 1993; Chen et al. 1994). Another possibility is that the radio lobes around 1E 1740.7–2942 are extragalactic (e.g., Phinney 1992), but Mirabel & Rodriguez (1993) have recently detected changes in the flux density of the radio lobes at the 3σ level which suggest that the source is closer than 17 kpc.

One way to establish the Galactic origin of 1E 1740.7–2942 would be to prove a physical connection between the X-ray source and the molecular cloud. A drawback of previous

observations of the molecular cloud is that they were made with single-dish telescopes and have moderate to poor angular resolution. To explore the relationship between 1E 1740.7–2942 and the molecular cloud, we undertook interferometric observations in the HCO^+ (1 → 0) line. HCO^+ is believed to be a tracer of energetic outflows in molecular gas (e.g., Garden & Carlstrom 1992), and we hoped to detect HCO^+ emission from the vicinity of the radio lobes around 1E 1740.7–2942. In § 2 we describe the observations, and in § 3 we discuss the images we obtained and their implications for the Great Annihilator.

2. OBSERVATIONS AND RESULTS

We observed HCO^+ (1–0) line emission from 1E 1740.7–2942 using the Owens Valley Radio Observatory (OVRO) millimeter interferometer. The primary beam width of the 10.4 m OVRO antennas ($65''$ FWHM) was only slightly larger than the $1'$ extent of the radio jets (Mirabel et al. 1992), so we used four overlapping pointings to map the field around 1E 1740.7–2942. We observed two of the four fields during the period 1992 December–1993 July when the array consisted of four dishes with cryogenically cooled SIS receivers. The two pointings ($\alpha = 17^{\text{h}}40^{\text{m}}42^{\text{s}}.5$, $\delta = -29^{\circ}43'15''$ and $\alpha = 17^{\text{h}}40^{\text{m}}43^{\text{s}}.5$, $\delta = -29^{\circ}43'40''$, epoch 1950.0) were centered on the VLA jets and offset by about $\pm 15''$ from the X-ray core. We alternated 5 minute integrations between the two phase centers, observing the nearby point source NRAO 530 every 20 minutes to monitor the phase behavior of the array. The absolute flux scale was determined from observations of Uranus and Neptune. We observed 3C 273 ($S = 26.2 \text{ Jy}$) for at least 15 minutes per transit to obtain a high signal-to-noise passband calibration. The total on-source integration time was 8 hr per field, and the average single-sideband system temperature was 640 K.

In 1993 September we observed two more pointings offset from the X-ray source by $\approx 30''$ west and northwest, respectively; the phase centers were $\alpha = 17^{\text{h}}40^{\text{m}}44^{\text{s}}.0$, $\delta = -29^{\circ}43'00''$ and $\alpha = 17^{\text{h}}40^{\text{m}}45^{\text{s}}.0$, $\delta = -29^{\circ}43'25''$. By 1993 September the interferometer had been upgraded to five elements, but otherwise the equipment and observing pro-

cedures were the same as before. The total integration time per field was 2.4 hr, and the mean single-sideband system temperature was 480 K.

During the observations we operated a digital spectrometer divided into two bands. A 32 MHz (108 km s^{-1}) band with 128 frequency channels was centered on the HCO^+ transition frequency (89.189 GHz) and Doppler shifted to an LSR velocity of -140 km s^{-1} . A second, lower resolution band with 128 MHz bandwidth (431 km s^{-1}) and 128 frequency channels was Doppler shifted to -40 km s^{-1} . The high-resolution band was centered on a strong HCO^+ line observed by Mirabel et al. (1991) using the IRAM 30 m telescope. The low-resolution band covered the velocity range -200 to $+100 \text{ km s}^{-1}$, where other molecular species have been detected in the direction of 1E 1740.7–2942 (Mirabel et al. 1991).

We calibrated the data using software specific to the OVRO millimeter interferometer and imaged each of the four fields using the Astronomical Image Processing System (AIPS). Although the data for the first two and the second two fields were obtained with different numbers of telescopes and array configurations, the u - v coverage was very similar for the four data sets. Natural weighting of the visibility data gave a $17'' \times 7''$ CLEAN beam at position angle 6° for each field.

There was strong HCO^+ emission at velocities near -140 km s^{-1} in each of the four images. Figure 1 shows the low-resolution HCO^+ spectrum averaged over areas of all four images where the line was above the noise. We integrated the image cubes over the velocity range -142.5 to -125.7 km s^{-1} where the line emission was strongest, and we mosaicked the four images using standard AIPS tasks. Figure 2 shows the resulting image.

In Figure 2 the three plus signs correspond to the tip of the northward-pointing VLA radio jet, the flat-spectrum radio core, and the tip of the southern jet, respectively. The HCO^+ emission does not coincide with the location of 1E 1740.7–2942, but it does lie along a ridge $15''$ to the west, oriented roughly parallel to the jets. The high-resolution HCO^+ spectra (not shown) indicate a slight velocity gradient along the ridge. As one moves south from the northern tip of the ridge the velocity of the HCO^+ line increases from -142 km s^{-1} to -138 km s^{-1} over a distance of $50''$ (2 pc at the Galactic center). The southernmost part of the ridge—a single-

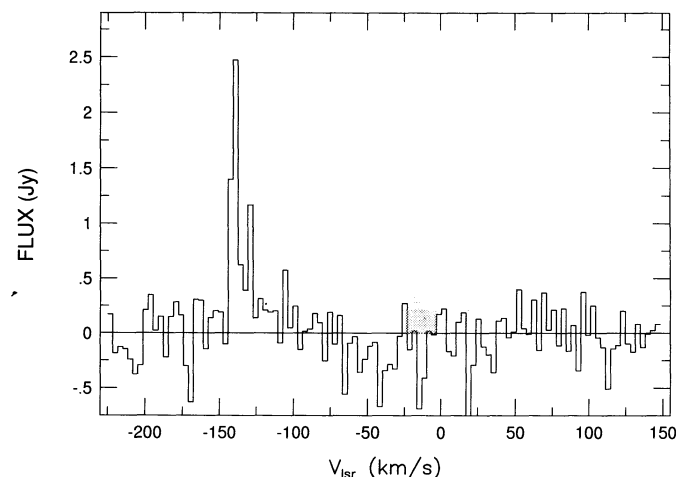


FIG. 1.— HCO^+ spectrum of 1E 1740.7–2942 obtained with the OVRO millimeter interferometer.

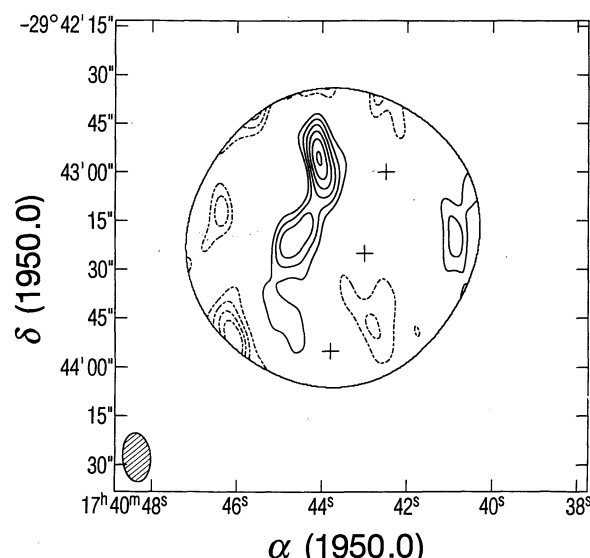


FIG. 2.—The HCO^+ emission integrated over the velocity range -142.5 to -125.7 km s^{-1} . The crosses mark the location of the central component and the two lobes of the radio counterpart to 1E 1740.7–2942. The image is a mosaic of four overlapping pointing centers around 1E 1740.7–2942. Before mosaicking, the images of the four pointing centers were corrected for the Gaussian response of the $65''$ primary beam with the result that the noise at the edge of the final image ($\text{rms} \approx 30 \text{ mJy beam}^{-1}$) was 1.5 times higher than the noise at the center (20 mJy beam^{-1}). The brightness contours are at -100 , -80 , -60 , -40 , 40 , 60 , 80 , 100 , 120 , and $140 \text{ mJy beam}^{-1}$. The deep negative features in the map are indicative of extended emission which was “resolved out” by the interferometer. Comparing our image to the IRAM map of HCO^+ emission, we find the total flux in the synthesis image is $\lesssim 20\%$ of that in the single-dish map.

contoured “blob” near the lowest plus sign in Figure 2—is at a velocity of -130 km s^{-1} . It may therefore be a clouddlet which is not associated with the rest of the ridge but appears to be so in projection along the line of sight.

3. DISCUSSION

Figure 2 clearly shows that there is no detectable HCO^+ emission near the radio lobes or the X-ray source. In this section we discuss whether the absence of HCO^+ emission is consistent with 1E 1740.7–2942 being the Great Annihilator.

Krolik & Kallman (1983) have considered molecular cloud chemistry in the presence of ionization from embedded X-ray sources. They found that X-ray chemistry is very much like cosmic-ray powered chemistry in that it is the secondary electrons from X-ray ionizations which perform most of the chemically important ionizations. Consequently, the important factor in assessing molecular abundances is the ionization rate. Although they were concerned with sources of soft X-rays (primarily stellar), their results are applicable here because the molecular cloud is optically thin at high energies, and soft X-rays ($E \lesssim 1 \text{ keV}$) will be most important for the chemistry of the cloud.

At low to moderately high ionization rates, $\xi \lesssim 10^{-15} \text{ s}^{-1}$, the abundance of HCO^+ increases with increasing ionization rate. However, at very high ionization rates, $\gtrsim 10^{-14} \text{ s}^{-1}$, the HCO^+ abundance begins to decrease with increasing ionization rates (Krolik & Kallman 1983). Hence, a possible explanation for the lack of HCO^+ emission in the neighborhood of 1E 1740.7–2942 is that a sufficiently high ionization rate either destroys any existing HCO^+ or inhibits its formation.

We have calculated the ionization rate in the neighborhood of 1E 1740.7–2942. Our model assumes that the emergent spectrum of 1E 1740.7–2942 is that of a Comptonized disk (Fig. 6 of Churazov 1993) and that the source is surrounded by molecular hydrogen of uniform density, n_{H} . We used approximations for the ionization cross section of H₂ given by Brown & Gould (1970) and Kwan & Krolik (1981), and we used the approximate expressions given by Shapiro, Lightman, & Eardley (1976) to calculate the emergent spectrum from the disk.

As we have already discussed, most of the ionization is due to softer photons, less than 1 keV, about which little or no information exists. Hence, we shall be forced to extrapolate this spectrum to much lower energies. Provided that the spectrum continues to increase to lower energies, rather than levelling off or falling, we expect our conclusions to be reasonably robust. Note that an implicit assumption of a Comptonized disk spectrum model is that there exists a central source which produces a copious number of photons well below the lower limit at which 1E 1740.7–2942 has been detected, ≈ 10 keV. Hence, to the extent that the Comptonized disk spectrum is an accurate model for 1E 1740.7–2942, our ionization rates may be underestimates, potentially by a large factor.

The ionization rate as a function of distance from the X-ray source is shown in Figure 3 for various ambient atomic hydrogen densities. For a dense cloud, $n \sim 10^4$ to 10^5 cm^{-3} , the ionization rate drops to 10^{-15} s^{-1} about 1 pc from the X-ray source. This is in good accord with the projected separation we observe between 1E 1740.7–2942 and the HCO⁺ ridge, $15'' \approx 0.6$ pc at the Galactic center. Given the numerous uncertainties in the problem, we regard this agreement with our observations as remarkably good. If this model is correct, one might expect HCO⁺ emission to the east as well as to the west of the X-ray source. We believe that the absence of emission to the east of 1E 1740.7–2942 is because the X-ray source is located near the eastern edge of the cloud (Mirabel et al. 1991).

These ionization rates are not sufficiently high to produce any substantial fractional ionization. We estimate that the gas in the neighborhood of 1E 1740.7–2942 should be neutral to a few parts in 10^4 , assuming a nominal density and temperature of 10^5 cm^{-3} and 10^4 K (Lingenfelter & Ramaty 1988). This estimate is consistent with the radio continuum observations

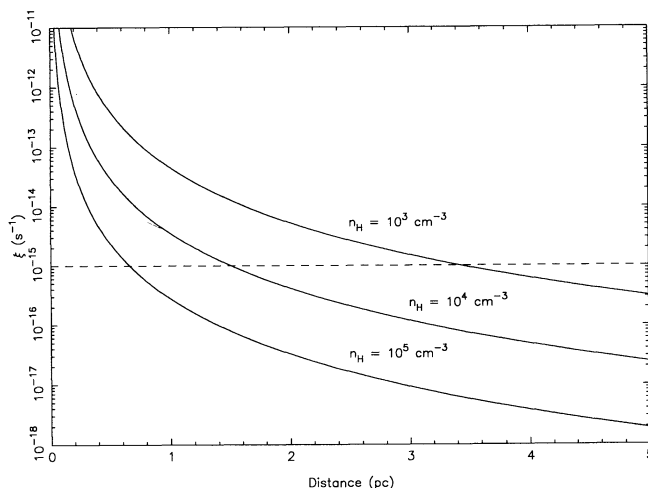


FIG. 3.—The ionization rate as a function of distance from 1E 1740.7–2942. The dashed horizontal line indicates the order of magnitude ionization rate for which HCO⁺ production is enhanced. For a cloud with uniform density 10^5 cm^{-3} we would expect to see an enhancement of HCO⁺ abundance ≈ 0.7 pc from the X-ray source, which is in good accord with what is observed.

of Mirabel et al. (1992) and Anantharamaiah et al. (1993), who found no H II region near 1E 1740.7–2942. Hence, this cloud could serve as the cold, dense annihilation region for the Great Annihilator.

A more conclusive link between the molecular cloud and 1E 1740.7–2942 could be obtained by imaging the field around 1E 1740.7–2942 in the lines of molecules which have enhanced abundances in high-ionization environments. Millimeter-wavelength transitions of CN and HCN⁺ are ideal for this purpose. Krolik & Kallman (1983) discuss these and other molecules marked by increasing abundances even at ionization rates as high as 10^{-13} s^{-1} . The detection of such molecules near the core of 1E 1740.7–2942 would definitively establish the Galactic origin of this object.

We thank Paul Goldsmith for helpful discussions. This work was supported by NSF grant AST 90-16404.

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